Grain Orientation Measurement of Passivated Aluminum Interconnects by X-ray Micro Diffraction

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Abstract. The crystallographic orientations of individual grains in a passivated aluminum interconnect line of 0.7-μm width were investigated by using an incident white x-ray microbeam at the Advanced Light Source, Berkeley National Laboratory. Intergrain orientation mapping was obtained with about 0.05º sensitivity by the micro Laue diffraction technique.

INTRODUCTION

The steady, continuing trend of miniaturization of electronic components in integrated circuits has placed stringent demands on interconnects between the circuit elements. Smaller interconnect cross-sections lead to extremely high current densities. The performance of these interconnects (usually Al-Cu or Cu) is of major concern to the Semiconductor Industry (1). Failure can arise from two main causes. First, as the dielectric encapsulated (passivated) interconnect cools from its deposition temperature, the metal will contract more that the silicon substrate and passivation layer, placing the metal under tensile stress orders of magnitude greater than its yield stress. Some dislocation motion will occur to relieve this stress, but the encapsulation prevents further relaxation. Stresses in an Al line can be as high as 400 MPa. Some relaxation also occurs by vacancy flow and this can result in stress voids that reduce the cross section of the line. The second failure mode, and by far the most important, is electromigration in active circuits (2). Atoms in the metal interconnects are acted on by a force due to the high electron current density and are actually moved from the cathode end of the line to the anode. Over time in a passivated interconnect, the motion of atoms down the line leads to compressive stresses building at the anode and tensile stresses at the cathode. Void formation can result due to the depletion of material at the cathode, leading to open circuit failure. Since electromigration is a diffusive process, stress gradients in the line (3,4), as well as the grain boundary structure and orientation (5), influence the time until failure of the interconnect.

It is important, therefore, to understand these failure mechanisms in a fundamental manner. So far the tools to accomplish this in a meaningful, quantitative way on individual lines have not been available. The key experiments required are (a) grain orientation measurements of individual grains in lines and (b) accurate strain measurements in individual grains along a line with and without current flow in the line. The only tool that can accomplish both these objectives on passivated interconnects is x-ray diffraction using suitably prepared x-ray beams. With the availability of Modern Third Generation high brilliance synchrotron source, we have for the first time the capability of producing micron and submicron x-ray beam with sufficient intensity to do meaningful orientation and strain measurements on individual interconnect lines.

EXPERIMENTAL

We have used bend magnet radiation from the synchrotron source at the Advanced Light Source. At the source point, the size is 300×30 μm^2 FWHM (horizontal and vertical) and is imaged with demagnifications of 300 and 60 respectively by a set of platinum-coated, elliptically bent, Kirkpatrick-Baez (K-B) focusing mirrors. Imaged spot sizes on the sample are about a micron in size. Photon energy is either white or monochromatic (energy range 6-14 keV), generated by inserting a pair of Si(111) channel-cut monochromator crystals into the beam path. A property of the four-crystal monochromator is its ability to direct the monochromatic primary beam along the same direction as the white radiation. Thus, the sample can be irradiated with either white or monochromatic radiation while maintaining the focal spot on the sample. White radiation is chosen for Laue experiments that determine crystallographic orientation and monochromatic radiation is chosen for d-spacing measurements in strain determination of single grains in the metal line. We will only

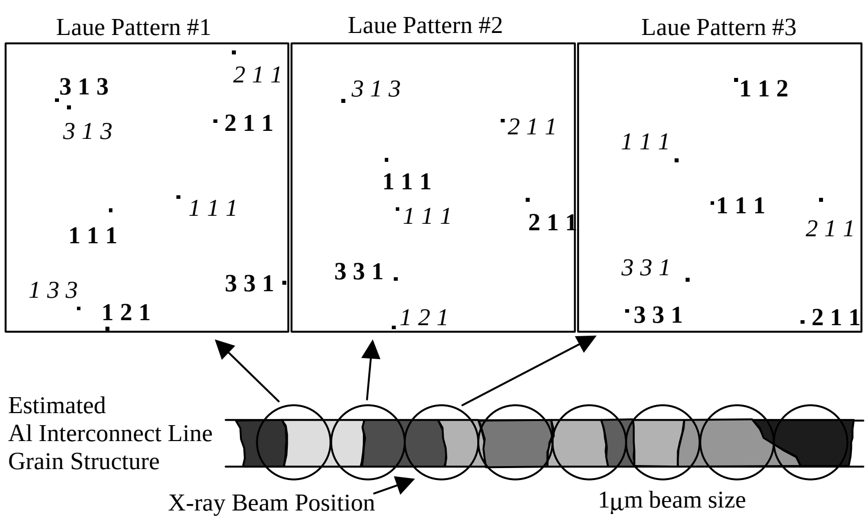

FIGURE 1. Three Laue patterns taken at 1 μm intervals along the Al interconnect line. The estimated Al grain structure is shown below the Laue patterns with x-ray beam position indicated. For each x-ray beam position, the leftmost grain is indexed in bold type, and the right most grain is indexed in italics.

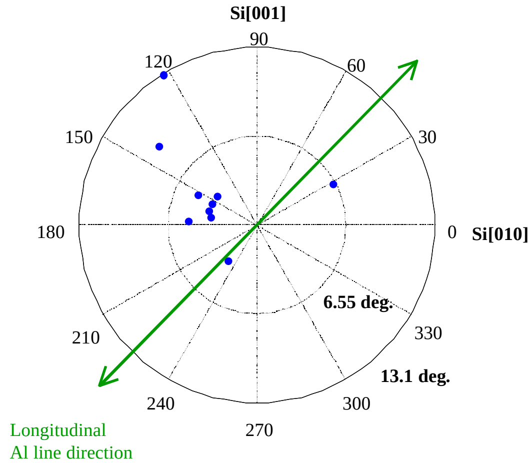

FIGURE 2. Al(111) orientations of aluminum grains (circular dots) relative to longitudinal line direction and silicon substrate.

discuss our initial results involving crystallographic orientation determinations.

The focused x-ray microbeam measurements were performed on an aluminum line deposited to 0.75-µm thickness and 0.7-µm width on an oxidized silicon substrate. The line was passivated with a one micron thick layer of SiO_2. The sample was mounted on a 0.05-µm resolution x-y translation stage, and x-ray microbeam measurements were made by translating along an interconnect line in a 1-µm step scan. Laue patterns were collected using white radiation and an x-ray CCD camera. The exposure time was 1 second and sample-to-CCD distance was 19.6 mm. Details of the experimental arrangement are described elsewhere (6).

The origin on the CCD detector array was determined by moving the CCD camera in the radial direction from the sample and recording the silicon Laue patterns at various distances from the sample. The origin was determined on the CCD where the lines drawn through the succession of the same Laue spots intersected. All aluminum spot positions were coordinated to the origin and indexed by using an automated indexing computer code. From the indexation of the aluminum pattern as well as the silicon crystal substrate, the orientation of aluminum grains was determined in an accuracy of ~0.05º.

RESULTS

Figure 1 shows the results of a grain orientation scan in the passivated aluminum interconnect wire. The background silicon Laue pattern is constant as the line is translated because the silicon is a single crystal substrate. The aluminum Laue pattern was obtained following digital subtraction of the silicon pattern from the silicon and aluminum pattern (7). In the schematic diagram of the grain structure as shown in Figure 1, it is assumed that the wire has a bamboo or near-bamboo structure. The positions of the grain boundaries in the interconnect were estimated from the intensities of the Laue spots. The out of plane misorientation of adjacent aluminum grains ranges from 0.5º to 10º. Figure 2 shows Al(111) orientations of the aluminum grains relative to the longitudinal aluminum line direction as well as the silicon substrate. The circle at 6.55º indicates that (111) orientations of most grains are within this range. The longitudinal line direction lies along [011] direction of the silicon substrate crystal. The majority of misorientation angle ranges between 3º and 4º and one grain shows a large angle of ~13º. Initial work shows that the in-plane grain orientation is random.

CONCLUSION AND FUTURE DEVELOPMENT

We have demonstrated that x-ray micro-diffraction is capable of determining the crystallographic orientation of individual grains in passivated metallic interconnect lines. The orientation mapping is performed by collecting the Laue patterns from individual grains along the length of the line and using a computerized indexing code. Beyond the work of orientation mapping, the requirement is to measure the d-spacing of various aluminum planes to determine the stress and strain state of individual grains along the length of the aluminum interconnect line. This question is currently being addressed with a specially designed, high absolute accuracy diffractometer.

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